Monitoring the Distribution of Submerged Aquatic Vegetation in Padilla Bay, NERR—SWMP Biomonitoring Pilot Site, 2004: FINAL REPORT

Douglas A. Bulthuis and Suzanne Shull
Padilla Bay National Estuarine Research Reserve

April 2006

A final report to Estuarine Reserves Division, OCRM, NOAA as partial fulfillment of Research & Monitoring Task 4 "Monitoring the Distribution of Submerged Aquatic Vegetation in Padilla Bay NERR—SWMP Biomonitoring Pilot Site, 2004" as part of the Operations Award for 2004-05 to Washington State Department of Ecology

Padilla Bay National Estuarine Research Reserve
Shorelands and Environmental Assessment
Department of Ecology
10441 Bayview-Edison Road
Mount Vernon, WA 98273

INTRODUCTION

The distribution of eelgrasses, macroalgae, and salt marshes in Padilla Bay have been mapped in the past (Bulthuis 1995, Shull 2000) but there are no studies monitoring the seasonal and year to year changes in the extent and distribution of these communities, nor in monitoring long-term trends in the distribution of these vegetative communities.

Eelgrasses are ecologically important, particularly in Padilla Bay. The total area covered by eelgrasses in Padilla Bay has been estimated at about 3,200 hectares, one of the largest contiguous stands of eelgrasses along the Pacific coast of North America (Webber et al. 1987, Bulthuis 1995, Shull 2000). Native eelgrass, *Zostera marina*, covered the greatest area in Padilla Bay, and the non-native eelgrass, *Z. japonica*, covered less area and occurred generally higher in the intertidal than *Z. marina* (Thom 1990, Bulthuis 1995, Shull 2000). The eelgrasses in Padilla Bay are predominately intertidal, extending from about -3.0 m up to about +0.8 m (Thom 1990, Bulthuis 1995, Dowty et al. 2005). Eelgrasses are the most extensive vegetative community in Padilla Bay and directly or indirectly support a diverse assemblage of fish (including juvenile Chinook and Coho Salmon), crabs (including the commercially and recreationally important Dungeness crab), waterfowl (including Black Brant and a subspecies which appears to winter in Padilla Bay) and many other vertebrate and invertebrate fauna (Dinnel et al. 1986, Simenstad et al. 1988, Reed et al. 1989, Dinnel 1990, Bulthuis 1996, Ray 1997, Dinnel 2000). Thus, knowledge of the distribution and interannual changes in the distribution and aerial extent of eelgrasses are critical to understanding the ecology of the bay, to understanding changes in the faunal communities in the bay, and to understanding ecological processes in Padilla Bay.

The general distribution of eelgrasses in Padilla Bay is known, having been mapped via satellite imagery (Webber et al. 1987), color aerial photography (Bulthuis 1995) and compact airborne spectral imagery (Shull 2000). However, interannual variation is expected in the distribution of eelgrasses, as has been documented for Chesapeake Bay (Moore et al. 2000). Bulthuis and Shull reported overall changes in the area covered by eelgrasses between 1989 and 2000 (Bulthuis and Shull 2002). In addition, in selected sub-areas of Padilla Bay, using historical aerial photos without ground reference data, large fluctuations in distribution within a few years were documented (Bulthuis and Shull 2002). Thus the distribution of eelgrasses in Padilla Bay is changing over the space of a decade and, apparently, fluctuating year to year. It is not known if the changes in distribution are part of a longer term trend or whether these are natural fluctuations in distribution. Two of the goals of this study were 1) to develop and test methods that can be used in a long-term monitoring program for interannual variation, and long-term trends in the areal extent, location and spatial pattern of submerged vegetation in Padilla Bay; and 2) to determine the areal extent, location, and spatial pattern of eelgrasses and macroalgae, in Padilla Bay in summer 2004.

Padilla Bay National Estuarine Research Reserve is one of 26 reserves in the National Estuarine Research Reserve System (NERRS). The reserves in the NERRS cooperate on a wide variety of programs including a System-wide Monitoring Program (SWMP). The goal of the SWMP is to identify and track short-term changes and long term trends in abiotic and biotic parameters in the reserves and land use and land cover changes in the watersheds of the reserves. The SWMP began in 1995 with measurement of a few physicochemical parameters of water quality and later added weather data collection and nutrient monitoring (Ross 2003). The SWMP is in the process of beginning biological monitoring with the first priority being submerged and emergent vegetation (Kennish 2004). Two aspects or “tiers” of monitoring estuarine vegetation have been identified: Tier 1 – monitoring the distribution and areal extent of submerged and emergent vegetation, and Tier 2 – monitoring selected vegetative characteristics in selected stands of submerged and emergent vegetation (National Estuarine Research Reserve System 2003). In response to the request for proposals, Padilla Bay National Estuarine Research Reserve applied for an award to adapt and apply methods that could be used to monitor distribution (Tier 1) of submerged vegetation in Padilla Bay. The present report is the final report for that award.

There are many methods for measuring distribution of submerged and emergent estuarine vegetation based on remote sensing platforms (e.g. airplane, satellite, boat) and image acquisition types (e.g. underwater videography, sidescan sonar, true color photography, infrared photography, compact airborne spectrographic imagery, and hyperspectral imagery) (Dobson et al 1995, Finkbeiner et al. 2001, National Estuarine Research Reserve System 2003). These various methods need to be evaluated for each application, vegetation type, and geographic location (Dobson et al 1995). Some of the important characteristics at Padilla Bay include the predominance of intertidal vegetation, variable water clarity during high tide, and high incidence of cloud cover throughout the year. These factors, among others, need to be evaluated and techniques developed in order to have a method that can be used on a regular basis over the long term for a monitoring program in a specific Reserve.

One of the objectives of the present study was to develop methods that could be used in a long-term monitoring program for determining the areal extent, distribution, and interannual variation of submerged vegetation in Padilla Bay. The primary questions to be addressed by annual monitoring of submerged vegetation in Padilla Bay are, “What are the patterns of inter-annual variability in the spatial distribution and areal coverage of eelgrasses and macroalgae in Padilla Bay?” and “What are the patterns of long-term change?”

METHODS

The distribution and extent of submerged and emergent estuarine vegetation in Padilla Bay were mapped using on-screen delineation and photo interpretation of true-color orthophotography guided by ground reference data collected in the field. Polygons representing the vegetated and non-vegetated areas were delineated and attributed in an ArcGIS 9.0 Personal Geodatabase (ESRI) schema. This section describes the methods used to conduct this project: image acquisition, image processing, classification schema and geodatabase construction, ground reference data, on-screen delineation, quality assurance/quality control checking of the data, and change detection between 2000 and 2004.

Image acquisition

Padilla Bay contracted to have true-color vertical aerial photographs taken on June 4, 2004 at an approximate scale of 1:12000 during a one-hour period around a predicted low tide of -1.2 m below MLLW (the lowest predicted tide of the year). The acquisition requirements were specified in a letter of request for quotes sent out to contractors several months in advance and included a table of specific date/time windows of optimal tides and a map of the extent of the study area. Sixty-four images were obtained in five flight lines with 60% overlap and 30% side lap.

Image processing

The contractor acquired 64 aerial photos of the bay (4 flight lines of 16 images) and produced 1:12000 scale (2.5cm=304.8m or 1”=10000’) contact prints of the photos after first making high resolution photogrammetric scans of the diapositive film. The images were scanned to digital files with a 0.15 m (6”) pixel resolution. The scanned images were processed using aerotriangulation (ORIMA software) in combination with the Global Positioning System (GPS) data from the aircraft, ground surveyed control, and image points (common points between photos and between the different flight lines) to mosaic the imagery. This process took images that had a relative geographic position (measured in feet with the GPS) and narrowed it to a more exact geographic position (measured in inches). For example, this process allows for measurements accurate to +/- 6 inches for a 1:12,000 or 1” = 1,000’ image. The Digital Terrain Model (DTM) was collected from the aerotriangulated images (using Socet Set and MicroStation software). The images and DTM were then used to create the orthorectified mosaic (corrected for camera lens distortion and topographic variations) in Socet Set (personal communication with Paul Hulzebos WSDOT). The imagery was projected to Washington State Plan Coordinate System, North Zone, NAD83 datum, U.S. Survey feet and then mosaicked and compressed into one Mr. Sid compressed file. Horizontal positional accuracy of the imagery was estimated to be + or – 0.3m (1’). In addition to NAD83 for the horizontal datum, NAV88 was used for the vertical datum.

Building the Geodatabase and classification scheme

The attribute classification scheme used in the present study was based on methods developed in two previous studies of the distribution of vegetation in Padilla Bay, from summer 1989 (Bulthuis 1991) and summer 2000 (Shull and Bulthuis, 2002). The geodatabase scheme was designed (based on work done by James Byrne of the NOAA Coastal Services Center) to meet Padilla Bay NERR’s need for mapping eelgrass (two species) and macroalgae in 2 categories of percent cover (11-50% and 51-100%), as well as salt marsh, bare substrate, and bare subtidal areas. The Geodatabase schema assigns behavior (using subtypes and domains) to the attribute fields of the delineated polygons using drop down selection boxes. This method helped maintain strict conformance to our mutually exclusive, totally exhaustive, hierarchical classification scheme (described in detail later in this section). The strict classification rules combined with the snapping and topological tools available from the geodatabase format provided an effective method that can be easily replicated in its application to other years of photography for change detection purposes and, in combination with an accuracy assessment, can be used for successful comparison to historical and/or alternative methods (Green and Congalton 2003). A minimum mapping unit of 0.1 hectare was used for all classifications except salt marsh. All detectable salt marsh was mapped.

The classification scheme was stored in fields of: Habitat, Zone, Rep_Species, Type, Cover, and Temp (Figure 1). The Habitat field was used to divide the data into integer subtypes of: 0=Unknown, 1=Bare, 2=Vegetated, 3=Upland (Figure 2). Each subtype had a separate set of rules for behavior and attributes. The default value for the subtype field was set to “Unknown”, however, all “Unknown” entries were assigned to one of the other subtype categories during the editing and quality control processing. The fields for Zone, Rep_Species, Type and Cover each had their own domain of values, described below. The Temp field was a text field added as a comment field for information about how that polygon was interpreted or to mark difficult to interpret areas to be reviewed later.

The domain of selectable values for each attribute field: “Zone”, “Rep_Species”, “Type”, and “Cover” is presented in Figure 3. Domain values for Zone were either intertidal or subtidal for any habitat type except upland which defaulted to <null>. Upland was included as a habitat category for terrestrial vegetation on island areas and for the upland fringe along the shore that occurred as a result of using higher resolution imagery in 2004 (0.5 m pixel resolution) overlaid with a standardized shoreline boundary derived from the lower resolution 2000 imagery (1.5 m (5') pixel resolution). The Rep_Species or "representative species" domain values were: *Zostera marina*, *Zostera japonica*, Algae, *Z. marina*/Algae mix, *Zj*/Algae mix, *Zm/Zj* mix, *Zm/Zj*/Algae mix, Logs, and NA. The Logs and NA classes were used for the Bare and Upland subtypes. All other classes were for the Vegetation Subtype (intertidal zone). An area assigned a field attribute value of *Zm*, *Zj*, or Algae could be a pure stand of that species or a greater than 51% composition cover of the standing vegetation. The mixed categories were visual estimates of areas where there was a 50% cover of each vegetation type or, in the case of the *Zm/Zj*/Algae Mix, a visual estimate of 33% of each vegetative type present. The Cover field had the following domain values: 51-100%. 11-50%, Bare, and NA. Bare areas had less than 10% vegetative cover. The hierarchical domains of the classification scheme are diagrammed for each of the subtypes: Upland (Figure 3a), Bare (Figure 3b), and Vegetated (Figure 3c).

Ground reference data collection

Ground reference data were collected at more than 1300 sites in Padilla Bay during approximately 40 days of field work between June and September, 2004 (Figure 4). Most sites were accessed by foot during low tide. The remaining sites were accessed by boat with visual inspection of the vegetation through the water column. At each site a geographic coordinate was acquired using a Trimble GeoExplorer II, a Garmin 12, 12XL or GPSMap 60C Global Positioning System. The Trimble data were post-processed to better than 1m accuracy using the county GPS base station data. Position averaging with the Garmin GPS units at each site produced calculated precision of better than 5m for the measured positions. WAAS capability on the GPSMap 60C rendered better than 1 meter accuracy for points when WAAS signal was available.

Field data forms were designed to be filled out on site by the field crew to make data collection as objective and consistent as possible. At each site a visual assessment was made based on a 10m by 10m plot size. Most of the sites were visited during low tide when eelgrass leaves are lying horizontally on the sediment surface. Each record of the field data contains information describing the plot: "transition" or "within a larger" habitat, type of vegetation, percent of the sediment surface covered by vegetation, percent composition of visible vegetation, date, time, GPS unit/waypoint number, digital photo number, and comments. More than 900 digital photos were taken in the field to document field sites during the reference data acquisition. The digital photos and the GPS track log were downloaded at the office and, using the third party extension (Pixpoint by Red Hen System) the photos were automatically linked in ArcMap to their GPS locations based on time.

On-screen delineation

Delineation of the vegetated and bare areas was done on-screen using a touch-screen display. A dual monitor permitted the use of a second display for the attribute table information to maximize the delineation work area. Editing was done in the Geodatabase using snap tolerance of 0.5' for edge and vertex on the edit layer, as well as, snapping to the year 2000 shoreline polygon (Shull and Bulthuis 2002). This study area polygon extends from the shoreline to the subtidal and provides a standard study area of delineation for comparisons to datasets from other years. At the end of each day after features were created and deleted, the database was compacted to dramatically reduce the file size (i.e. 36Mb to 12Mb).

Interpretation of the aerial photography was done from the digital display with ground reference data points overlaid (labeled with type and percent cover), and active links from the reference data table to the digital images taken in the field (Figures 4 & 5). A Peak Zoom Lupe 816 Lens was used with the contact prints to better interpret the data using context, hue, and texture characteristics of the prints which often were lost in the digital display or along seams of mosaicked imagery. The display of the imagery was often improved using digital enhancements such as a standard deviation stretch or false color-IR (reversal of band display). A Z/I Digital Mapping Camera (DMC) airborne image with a Near IR band was taken of Padilla Bay on July 28, 2004 (0.3m resolution), as part of a separate NOAA project. The IR band of this dataset was particularly useful in interpreting the *Z. japonica* and macroalgae areas.

Quality Assurance/Quality Control

Another advantage of the Geodatabase format is the use of topology rules. The topology rules "Must not have gaps" and "Must not have overlap" with a default cluster tolerance of 0.0006' found 51 errors. All sliver polygons with areas less than 0.01 were merged with adjacent polygons (unless they were salt marsh) and gaps were fixed using the topology tool. The Multipart to Singlepart GeoProcessing Tool was used to assure that there was only one polygon per record. A new field was added to the final "singlepart" dataset and a unique classification id number representing generalized classes (all percent cover and 50%/50% composition of eelgrass with algae were merged) to correspond with the 2000 dataset classes (Table 1).

Change Detection Method

To map areas of change between 2000 and 2004, the two years were combined with the Geoprocessing Tool – "Intersect". A change field was added to the resulting dataset and the values of the change field were calculated: change = 2000 generalized classification ID minus the 2004 generalized classification ID. All values of 0 were areas where no change occurred between years. The full classification field values in combination with the change field enabled the production of maps showing areas where: bare areas had become *Zostera* or Algae areas had become *Zostera*, *Zostera* areas had become bare or Algae, and *Zostera marina* had become *Zostera japonica* or *Zostera japonica* had become *Zostera marina*.

RESULTS

Development and testing of methods

One of the objectives of the present study was to develop and test methods that could be used in a long-term monitoring program for determining the extent, distribution, and interannual variation of submerged vegetation in Padilla Bay. The methods developed and used in this study were effective. These methods utilized true color aerial photography acquired during an extreme low tide, a photomozaic of the 64 aerial photos, orthorectification of the photomozaic, extensive ground reference data collection at more than 1000 sites, and on-screen delineation guided by the ground reference data. These methods are appropriate for monitoring the distribution of estuarine vegetation in Padilla Bay as part of the NERRS System-wide Monitoring Program. Vegetated and non-vegetated areas were accurately delineated from the aerial photographs and ground reference data. Distribution of *Zostera marina* was distinguished from *Z. japonica* based mainly on the ground reference data. These overall methods were based on widely accepted and recommended methods (e.g. Dobson et al. 1995, Finkbeiner et al. 2001) with adaptations using a

Geodatabase design and extensive ground reference data collection. The study was carried out primarily by Padilla Bay NERR staff with contracted services for obtaining the aerial photos and for orthorectification and mosaicking of the photos.

Distribution of estuarine vegetation

Another objective of the present study was to determine the extent and distribution of eelgrasses, macroalgae, and salt marshes in Padilla Bay during the summer of 2004. The distribution of generalized classes of estuarine vegetation in Padilla Bay is presented in Figure 6. The vegetated areas were classified into different categories and delineated as polygons based on which vegetation contributed the most to the percent cover. Within the polygons for each vegetation type, other species may have been present either intermixed or in patches up to the size of the minimum mapping unit (0.1 ha). In places there were bare patches within the vegetated polygons, but always less than the minimum mapping unit. Polygons, thus, were heterogeneous units with bare patches and other species intermixed, but always with one species or vegetation type the predominate percent cover. For example, *Zostera marina* polygons often contained areas in which macroalgae were growing among the *Z. marina* shoots and/or contained macroalgal mats smaller than 0.1 hectares (minimum mapping unit). *Z. marina* polygons sometimes contained *Z. japonica* patches smaller than 0.1 hectares. Thus, the polygons designated *Z. marina* sometimes contained a variety of macroalgae, *Z. japonica*, and other vegetation; but these areas have in common the fact that *Z. marina* contributed more than any other vegetation type to the overall percent cover of vegetation.

There were many areas in Padilla Bay where the two *Zostera* species intermixed. In some of these areas the two species were extensively intermingled with individual plants of the two species growing together. In most areas, however, the two *Zostera* species grew in mono-specific patches with small patches of the non-dominant cover type scattered in an area generally dominated by the other species. In addition there were some areas in which the two *Zostera* species contributed about equally to the vegetative cover. These areas were categorized as a mix of the two species (Figure 6).

Macroalgae were intermixed in the eelgrass beds. In addition, there were patches in which algae contributed the most to the percent cover of vegetation. In these patches either or both *Z. marina* and *Z. japonica* were sometimes present, but the macroalgae were the largest contributor to the vegetative cover. These patches were distributed throughout the bay, but especially on the higher intertidal flats in the southern part of the bay and on raised patches in mid-bay. The algae were mainly Ulvaceae of the genera *Enteromorpha* and *Ulva.*

Z. marina was extensively distributed throughout the intertidal below MLLW. *Z. marina* extended in the subtidal in bands along the channels that dissect the intertidal flats and along the channels that border Padilla Bay on the west. *Z. japonica* dominated areas occurred higher in the intertidal and were usually distributed on the shoreward side of the *Z. marina* dominated areas throughout most of the bay (Figure 6). There was little *Z. japonica* on the intertidal flats adjacent to March Point.

In addition to the submerged aquatic vegetation in Padilla Bay (eelgrasses and macroalgae), the methods were also effective in delineating intertidal salt marshes. Salt marshes in Padilla Bay were confined to pockets or linear strips along the shore between the dikes or upland and the bare intertidal flats. Often the salt marsh patches were smaller than the minimum mapping unit (0.1 hectare). However, these areas were delineated because the sum of these small patches make up a significant proportion of the total salt marsh cover (two hectares in 47 polygons) in Padilla Bay and provide a habitat structure in otherwise bare intertidal flats. The salt marshes were composed chiefly of *Salicornia virginica* and *Distichlis spicatum* plus one large (0.25 ha) patch of *Spergularia sp.*

Most of the area designated *Z. marina* or *Z. japonica* had vegetative cover greater than 50% (Figure 7). However, *Z. marina* of 11-50% cover was distributed in the central areas of Padilla Bay, often on intertidal flats slightly raised above the surrounding flats. *Z. marina* patches of 11-50% cover also were distributed widely on the intertidal flats in the southern end of the bay, near the upper limits of distribution (Figure 7). *Z. japonica* almost always occurred in stands with greater than 50% cover. In the upper intertidal, near the limits of distribution of *Z. japonica*, there were some areas of 11-50% cover (Figure 7).

The total area covered by *Zostera* species in Padilla Bay in 2004 was 3800 hectares (Table 2). Most of this area was covered with greater than 50% cover of vegetation; only 7% of the total eelgrass area was mapped as 11-50% cover. *Z. marina* was the predominant cover on about 3100 hectares, *Z. japonica* on about 500 hectares, and the two about equally present on 200 hectares. Macroalgae were the predominant cover on about 350 hectares. There were about 58 hectares of salt marsh in the bay.

DISCUSSION

Development and testing of methods

One of the goals of the present study was to develop and test an appropriate method for regular monitoring of submerged vegetation in Padilla Bay as part of the NERRS System-wide Monitoring Program. The methods developed and used in this project are consistent with the methods recommended by Dobson et al. (1995) and Finkbeiner et al. (2001). The aerial photography, orthorectification, and mosaicking of the aerial photographs were contracted out. The rest of the study was conducted by Padilla Bay staff including: the ground reference data collection, geodatabase construction, photointerpretation, and on-screen digitizing. Thus, estuarine vegetation in Padilla Bay can be monitored annually, or at other regular intervals, with the methods used in the present study.

The present method addressed some of the major challenges to monitoring distribution of submerged aquatic vegetation in Padilla Bay National Estuarine Research Reserve. One of the challenges was the extensive area covered by eelgrasses which require numerous aerial photographs without any upland for georeference. The present method contracted an aerial photo company to address this issue. The contractor acquired 64 photos (4 flight lines of 16 images) and then used a process of aerotriangulation (ORIMA software) in combination with GPS data from the aircraft, ground surveyed control and image points (common points between photos and between the different flight lines) to mosaic the imagery. The resulting positional accuracy appeared to be very good as indicated by good correspondence with other georectified upland images and by good correspondence with GPS readings collected during ground reference data collection with a variety of GPS units. Future monitoring of submerged vegetation in Padilla Bay using "in house" registration and rectification of aerial photos, could be implemented using the 2004 orthophotographs and DTM obtained in this project as the reference.

Another challenge in mapping estuarine vegetation in Padilla Bay that the present method addressed was differentiating between very low coverage vegetated areas and non-vegetated areas. The present method dealt with this issue by classifying percent cover less than 10% as bare, and by collecting extensive ground reference data in the upper intertidal on bare and low percent cover flats and by reference to ancillary infra-red aerial photographs of Padilla Bay.

A third challenge in mapping estuarine vegetation in Padilla Bay was delineating the subtidal edge of *Zostera marina*. Turbid or colored coastal water can prevent the deeper edge of *Z. marina* from being visible in aerial photographs. The present method dealt with this issue with extensive ground reference data collected with a vessel during an extreme low tide. The vessel ground reference data demonstrated that eelgrasses did not extend deeper than the apparent edge that could be delineated on the aerial photos.

A fourth challenge to mapping estuarine vegetation in Padilla Bay was distinguishing between the two species of *Zostera*. The two species, *Z. marina* and *Z. japonica*, could not be distinguished only by characteristics seen on the aerial photos. With extensive ground reference data, however, there were many areas where the line of distribution between the two species could be delineated. At times the line between the species followed a physiographic feature such as a change in elevation, a change in sediment characteristics, or the edge of a channel. Thus, the physiographic feature could be seen in the aerial photo and formed the basis for delineating between the two species. The ground reference data were used to determine which *Zostera* species contributed the most to the percent cover. In other areas, the two species were intermixed and/or the boundary between the species did not follow any distinguishable physiographic feature. When ground reference data were available, lines of demarcation were drawn between ground reference data sites. When ground reference data were not available, the species could not always be distinguished, and historical patterns of distribution and best judgment were used. This limitation of the capability of photointerpretation of color aerial photography to distinguish between the two species is important for Padilla Bay. *Z. japonica* is a non-native species that appears to be expanding its distribution throughout Washington and British Columbia and within Padilla Bay (Harrison and Bigley 1982, Bulthuis and Shull 2002, Hahn 2003). The distribution of the two species is one important parameter that Padilla Bay NERR should monitor, but requires ancillary data and methods in addition to color aerial photography.

Another similar challenge to mapping estuarine vegetation in Padilla Bay was distinguishing consistently between macroalgae and eelgrass. In most areas of macroalgae in Padilla Bay, photointerpretation reliably distinguished areas of macroalgae from *Zostera* spp. Both the tone of green color and the pattern or texture of macroalgae were different from eelgrass. However, in some areas of Padilla Bay, macroalgae were extensively intermixed with *Z. marina* and photointerpretation was difficult and delineation or designation of vegetation type relied mainly on ground reference data.

Algal mats and blooms of algae are ephemeral. The aerial photos were acquired in early June and the ground reference data were collected throughout June, July, August, and September. Some areas that showed bright green algae mats on the aerial photos in early June, were bare of any vegetation when they were visited for ground reference data collection in August. These observations emphasize the importance of acquiring ground reference data as close to the time of the aerial photographs as possible when mapping macroalgae.

The distribution of macroalgae in Padilla Bay is important and a characteristic that Padilla Bay NERR should monitor. Macroalgal mats have contributed to decline of eelgrasses (Den Hartog 1994, Hauxwell et al. 2001, Morris and Virnstein 2004, Verdelhos et al. 2005) in other parts of the world. Such mats are present in Puget Sound (Frankenstein 2000) and Padilla Bay (Bulthuis 1991, Bulthuis and Shull 2002) and should be monitored to provide an indication of any threat to eelgrasses in the bay.

These methods provide accurate distributional information of *Zostera* spp., macroalgae (Ulvaceae), and salt marshes in Padilla Bay in 2004. In addition to presence/absence of vegetation, the data include percent cover data in two categories, 11-50% and 51-100% cover.

Distribution of submerged aquatic vegetation in Padilla Bay

The present survey is the fourth detailed survey of the distribution of estuarine vegetation in Padilla Bay (Bulthuis 1991, Shull 2000, Bulthuis and Shull 2002). In the time since the previous surveys (1989, 1996, and 2000), the low cost technology available has continued to improve (Shull and Bulthuis 2002). Thus, the present distribution maps have a greater positional accuracy than the previous three surveys. When comparisons are made between the present study and previous surveys, any apparent differences need to be assessed as to whether they may represent slightly more accurate positional accuracy of the same “bed” of vegetation rather than a shifting distribution (Meehan et al. 2005). This was especially evident in the present study when comparing eelgrass beds along the edges of channels. It is expected that continuing improvements in the technology (e.g. GPS accuracy and finer scale) and Geographic Information System software will mean that monitoring of distribution of estuarine vegetation will need to continue to deal with these types of issues in the foreseeable future when making comparisons with earlier surveys.

In the present study *Zostera marina* was widely distributed in the intertidal in the central and western areas of Padilla Bay, extending to the channels and straits to the west of Padilla Bay. This broad distributional pattern is similar to that reported in previous detailed surveys of Padilla Bay (Bulthuis 1991, Shull 2000, Bulthuis and Shull 2002). The similarity in distribution and in the total area of *Z. marina* covered in Padilla Bay in the previous surveys indicates the overall stability of *Z. marina* in Padilla Bay over the last 15 years (1989 to 2004). This is particularly true for the lower intertidal and subtidal areas of distribution.

Zostera japonica was distributed mainly in the upper intertidal and generally in shallower areas than *Z. marina* (Figure 6). This general distribution is similar to previous surveys of Padilla Bay (Bulthuis 1995, Shull 2000, Bulthuis & Shull 2002). The locations of the areas covered by vegetation in the upper intertidal were more variable among survey years (1989, 1996, 2000, and 2004) than the mid- and lower intertidal. This may be caused by interannual variation in an area that is near the upper limits of distribution for the two species. Possible causes for such interannual variability include differences in desiccation stress from year to year because of differences in wind and temperature conditions during low tide. The pattern of interannual variation from an annual monitoring program of estuarine vegetation in Padilla Bay, would provide data to evaluate possible causes for the interannual variation. Monitoring selected areas within the growing season (e.g. June and August) could also indicate possible causes for interannual variation.

The present study indicates that eelgrasses cover about 3800 hectares of intertidal flats and subtidal bottoms in Padilla Bay (Table 2). This is very similar to the 3865 hectares of coverage estimated by Bulthuis and Shull (2002) in 2000 (Table 3), and somewhat more than the 3208 hectares estimated for 1989 (Bulthuis 1991). Bulthuis (1991) used a Zoom Transfer Scope method which usually results in overestimation of area covered compared to higher resolution photography and on-screen delineation (Meehan et al. 2005). Thus, the lower estimate of area covered by eelgrasses in 1989 is likely to be real, and not caused by methodological differences. Bulthuis (1991) indicated that the 1988-89 winter had been more severe than usual with accumulations of ice in the upper intertidal. Such ice sheets can scour eelgrass beds in bays that commonly have ice in winter (Robertson and Mann 1984) and may have done so in Padilla Bay during the winter of 1988-89. Several scientists who had worked a number of years in Padilla Bay commented on the lack of seagrasses during the spring and early summer of 1989 (see discussion in Bulthuis 1991). The similarity in total area covered by *Zostera* spp. in 2000 and 2004 (3865 hectares and 3800 hectares) is consistent with the hypothesis that 1989 was an unusual year with regard to total area covered by *Zostera* spp. The similarity in the estimated area covered between 2000 and 2004 (Table 3) is striking (within 2% of each other) and indicates a long term stability in the eelgrass distribution in Padilla Bay in recent years.

A detailed comparison of distribution of vegetation in 2000 and 2004 indicates that about 331 hectares of intertidal *Z. marina* was lost during that four year period with a gain of 254 hectares of subtidal *Z. marina* (Table 3). These apparent changes may be primarily artifacts of differences in the water height at the time of the aerial photos and delineation protocols. The distinction between intertidal and subtidal is generally based on whether the sediment surface is exposed during low water. However, with *Z. marina* leaves up to 2 m tall, the vegetation becomes a thick mat of overlapping leaves above the sediment as the water recedes. In most areas of dense and tall *Z. marina*, it is not possible to discriminate from the aerial photographs whether the water level is above the sediment surface or not. In some areas, the *Z. marina* leaves are clearly floating, but in other areas it is ambiguous whether the leaves are floating or lying over each other on the sediment surface. Therefore, the apparent difference in intertidal and subtidal *Z. marina* from 2000 to 2004 is unlikely to reflect a change in the distribution of *Z. marina*. However, the subtidal *Z. marina* is an important habitat in Padilla Bay, with a different assemblage of fauna and providing refuge for some nekton during low water (Dinnel et al. 1986, Ray 1997). Thus, subtidal *Z. marina* was delineated separately from intertidal *Z. marina*.

A detailed comparison also indicates an apparent loss of about 370 hectares of intertidal *Z. japonica* between 2000 and 2004 (Table 3). About half of this apparent loss is due to slightly changed categories in 2004. However, total area of *Z. japonica* declined by about 170 ha between 2000 and 2004 (Table 3). This "loss" may be due, in part, to areas where *Z. japonica* and *Z. marina* were both present in both years, but where *Z. marina* is now the predominant vegetation rather than *Z. japonica*. It is possible that *Z. japonica* is helping create suitable conditions for growth of *Z. marina*, particularly by retaining water on intertidal flats (Powell and Schaffner 1991). It has been suggested that such facilitation of *Z. marina* growth by *Z. japonica* has occurred in the Robert Banks, British Columbia area, about 100 km north of Padilla Bay (Durance, personal communication).

Native salt marsh covered about 58 hectares in 2004, of which 40 hectares had not changed between 2000 and 2004 (Table 3). Five hectares were lost to bare substrate but 15 hectares that had been mapped as bare in 2004, were mapped as native salt marsh in 2004. Better resolution, particularly for long narrow features, such as the native salt marsh along the shoreline or along Big Indian, Little Indian, and No Name Sloughs may be the reason that more salt marsh was mapped in 2004 than in 2000.

Padilla Bay, with 3800 hectares of eelgrass, contains one of the largest contiguous stands of eelgrasses in the Pacific Northwest and along the west coast of North America (Bulthuis 1995). Within greater Puget Sound (including the Strait of Juan de Fuca, the San Juan Islands, and Georgia Strait up to the United States border), Padilla Bay contains about 25% of all the eelgrass in this inland sea (Berry et al. 2003, Dowty et al. 2005). Other large stands of eelgrasses in the Pacific Northwest have been reported in Boundary Bay, British Columbia (Baldwin and Lovvorn 1994), Grays Harbor, Washington (Thom 1984), Willapa Bay, Washington, and Humboldt Bay, California (Barnhart et al. 1992).

The present study has demonstrated methods that can be used to monitor the distribution of estuarine vegetation in Padilla Bay. These methods are well established and are recommended methods (e.g. Dobson et al. 1992, Finkbeiner et al. 2001) that have been adapted for use in Padilla Bay. These methods could be used in a long-term monitoring program to determine the extent, distribution, interannual variation, and long-term trends of eelgrasses, macroalgae, and salt marshes in Padilla Bay. During the summer of 2004, estuarine vegetation included 3800 hectares of eelgrasses (*Zostera marina* and *Z. japonica*), about 60 hectares of native salt marsh, and 350 hectares of macroalgae mats (predominately Ulvaceae). The eelgrass beds in Padilla Bay are the largest extent of eelgrasses in greater Puget Sound and one of the largest stands along the west coast of North America.

ACKNOWLEDGEMENTS

Sincere thanks are due to Donna Ball and Erin Koshko who conducted the majority of the ground reference data collection, walking over the muddy and sandy intertidal flats of Padilla Bay during most low tides of the summer of 2004, taking notes, recording observations, photographing the sites, and recording GPS positions. The ground reference data they collected was critical in the photointerpretation. Sincere thanks are also due to Paula Margerum for skippering the vessels that brought Dona and Erin to water accessible ground reference sites and for bringing us to the "vessel" ground reference sites; to David Weinman who served as first mate on the vessels; to Paul Hulzeb, Washington Department of Transportation for ortho-processing of the aerial photographs; and to James Byrne for the framework for the Geodatabase that was developed in the present study. This project was financially supported through a grant to the Washington State Department of Ecology with funds obtained from NOAA/Office of Ocean and Coastal Resource Management and appropriated for Section 315 of the Coastal Zone Management Act of 1972, as amended.

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Table 1. A generalized classification category was used to enable the comparison between the 2000 and the 2004 surveys. A new field was added to the final datasets with a unique classification ID number to represent generalized classes (all the percent cover and 50%/50% composition of eelgrass with algae were merged) to corresponded to the merged percent cover classes of the 2000 dataset.

Year 2000 Classification ID	Generalized Classification	Year 2004 Classification ID
19	Upland	0
4,5,6	*Zostera marina*	1
1,2	*Zostera japonica*	2
10,11	Algae	3
13	Salt marsh	5
16	Bare Intertidal	16
17	Bare Subtidal	17

Table 2. Total area of submerged and emergent vegetation in Padilla Bay in June 2004. The distribution of these categories is shown in Figure 7.

Classification category	**Area (hectares) 2004**
Zostera marina intertidal 51-100%	2448
Zostera marina intertidal 11-50%	194
Zostera marina subtidal	471
Zostera marina/Algae Mixed intertidal 51-100%	17
Zostera marina/Algae Mixed intertidal 11-50%	1
Total *Zostera marina*	3131
Zostera japonica intertidal 51-100%	417
Zostera japonica intertidal 11-50%	53
Zostera japonica/Zostera marina Mixed intertidal 51-100%	155
Zostera japonica/Zostera marina Mixed intertidal 11-50%	20
Zj/Zm/Algae Mixed intertidal	15
Zj/Zm/Algae Mixed intertidal	9
Total *Zostera japonica*	669
Total *Zostera*	3800
Macroalgae 51-100%	263
Macroalgae 11-50%	88
Total Macroalgae	351
Salt marsh	58
Total Vegetation	4209
Intertidal bare	1156
Subtidal bare	836

Table 3. Total area of submerged and emergent vegetation in Padilla Bay in 2000 (Bulthuis and Shull 2000) and 2004 (present study) and the total gains or losses for each classification category.

Classification category	**Area (hectares) 2000**	**Area (hectares) 2004**	**Area (hectares) Gain or Loss**
Zostera marina intertidal 51-100%	2779	2448	-331
Zostera marina intertidal 11-50%	50	194	144
Zostera marina subtidal	217	471	254
Zostera marina/Algae Mixed intertidal 51-100%	-	17	
Zostera marina/Algae Mixed intertidal 11-50%	-	1	
Total *Zostera marina*	3046	3131	85
Zostera japonica intertidal 51-100%	722	417	-305
Zostera japonica intertidal 11-50%	114	53	-61
Zostera japonica/Zostera marina Mixed intertidal 51-100%	-	155	
Zostera japonica/Zostera marina Mixed intertidal 11-50%	-	20	
Zj/Zm/Algae Mixed intertidal 51-100%		15	
Zj/Zm/Algae Mixed intertidal 11-50%	-	9	
Total *Zostera japonica*	836	669	-167
Total *Zostera*	3882	3800	-82
Macroalgae 51-100%	124	263	139
Macroalgae 11-50%	80	88	8
Total Macroalgae	204	351	147
Salt marsh	47	58	11
Total Vegetation	4133	4209	76
Intertidal bare	1145	1156	11
Subtidal bare	926	836	-90

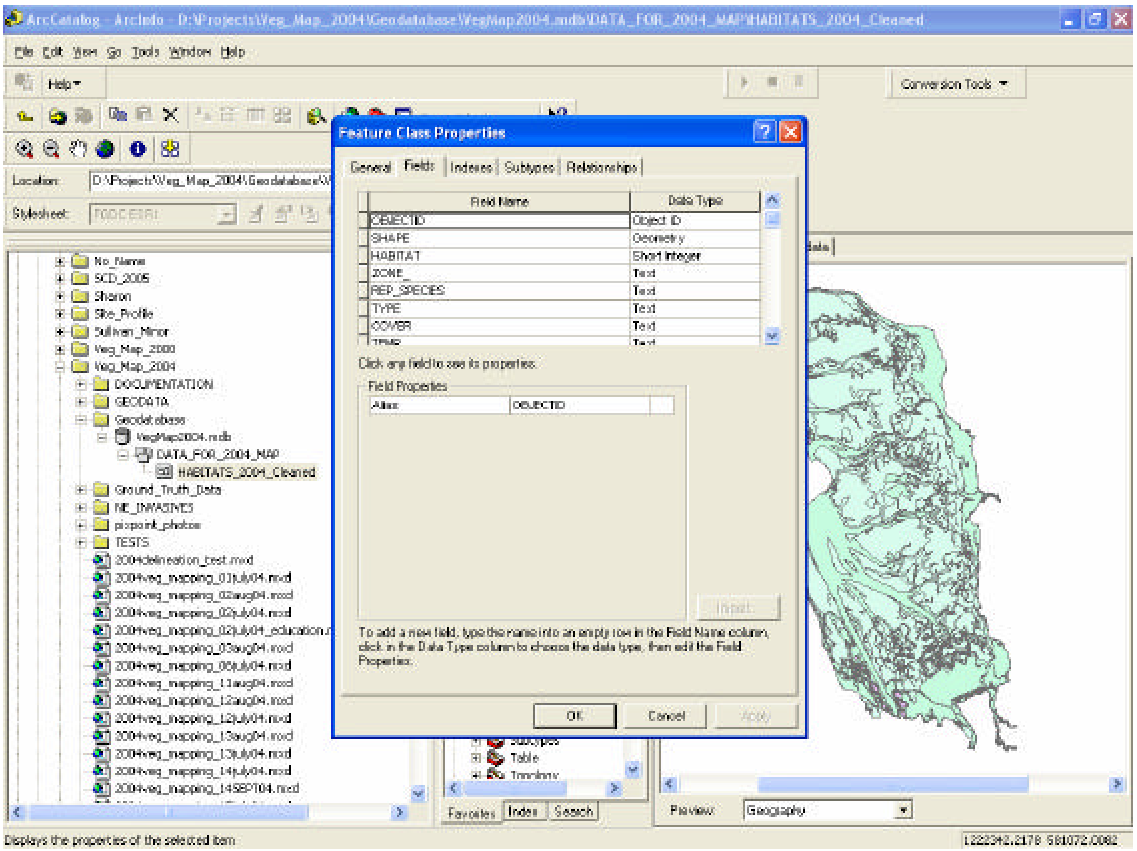

Figure 1. Field names and data types of the attribute table for the 2004 Vegetation Mapping Geodatabase for Padilla Bay, WA.

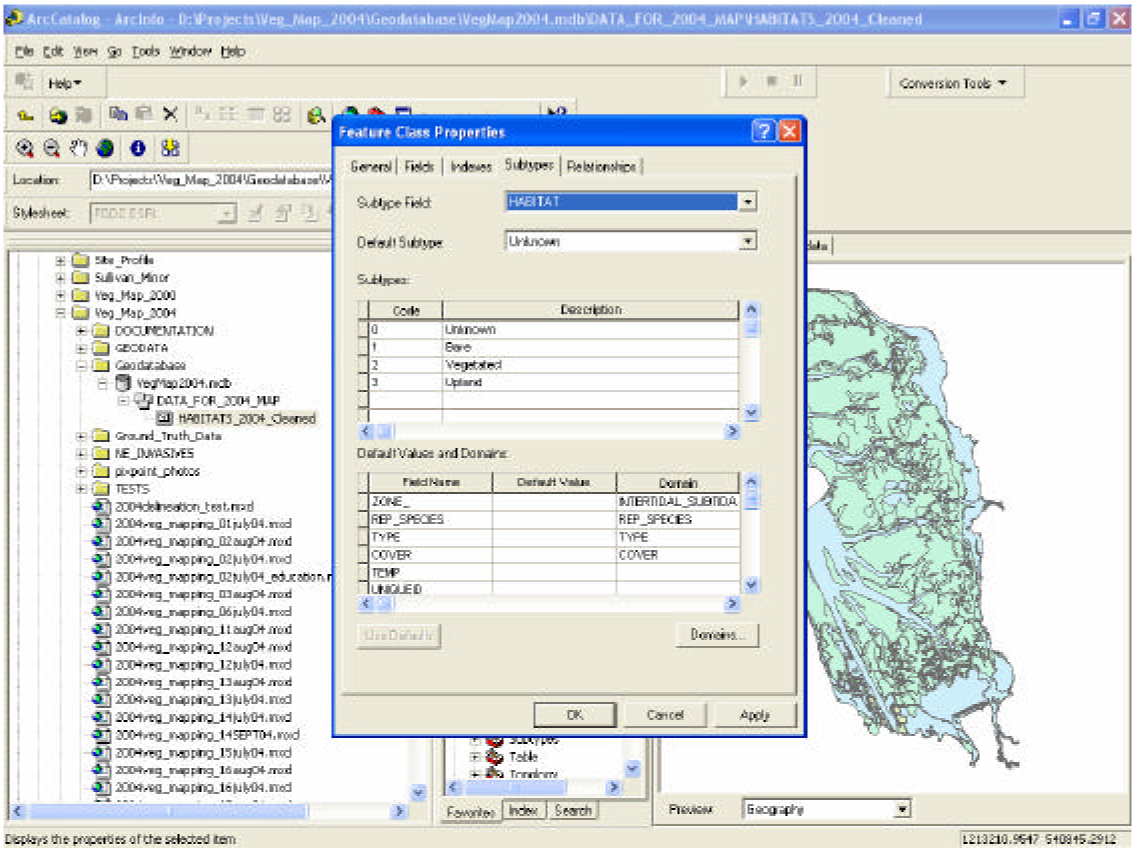

Figure 2. The first attribute field of the 2004 Vegetation Mapping Geodatabase for Padilla Bay, WA permits attribute values of “Unknown” (default value), “Bare”, “Vegetated”, or “Upland” as subtype integer coded values.

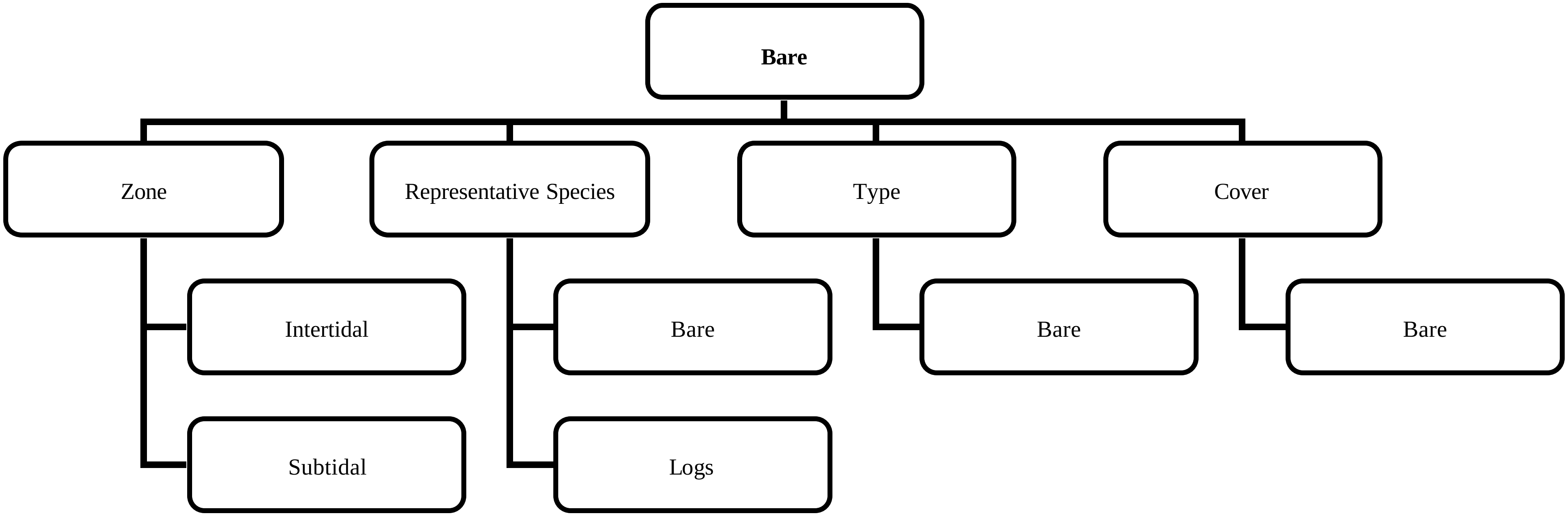

Figure 3a. Hierarchical diagram of domain values for the subtype “Bare” in the 2004 Vegetation Mapping Geodatabase for Padilla Bay, WA.

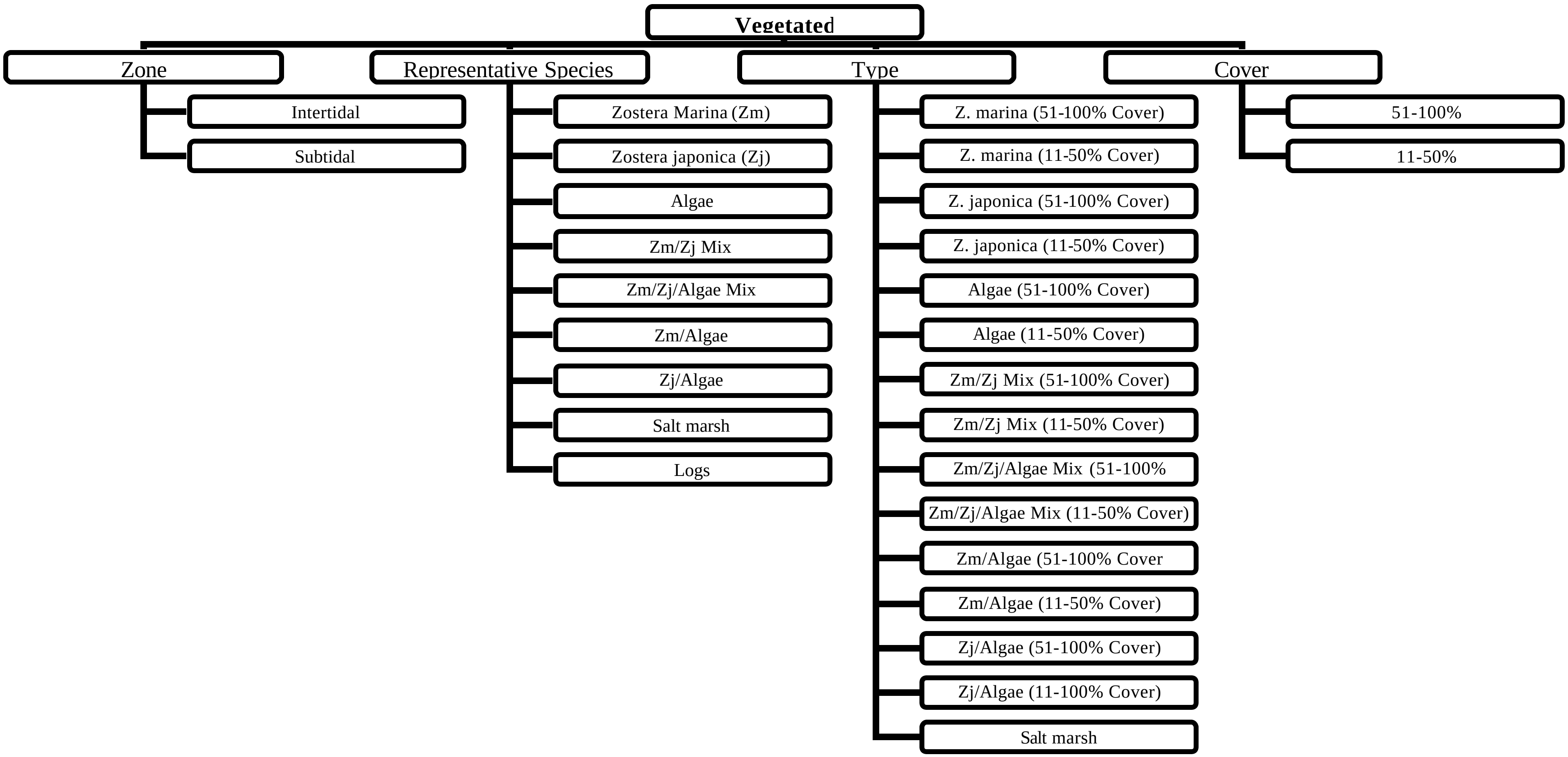

Figure 3b. Hierarchical diagram of domain values for the subtype "Vegetated" 2004 in the Vegetation Mapping Geodatabase for Padilla Bay, WA

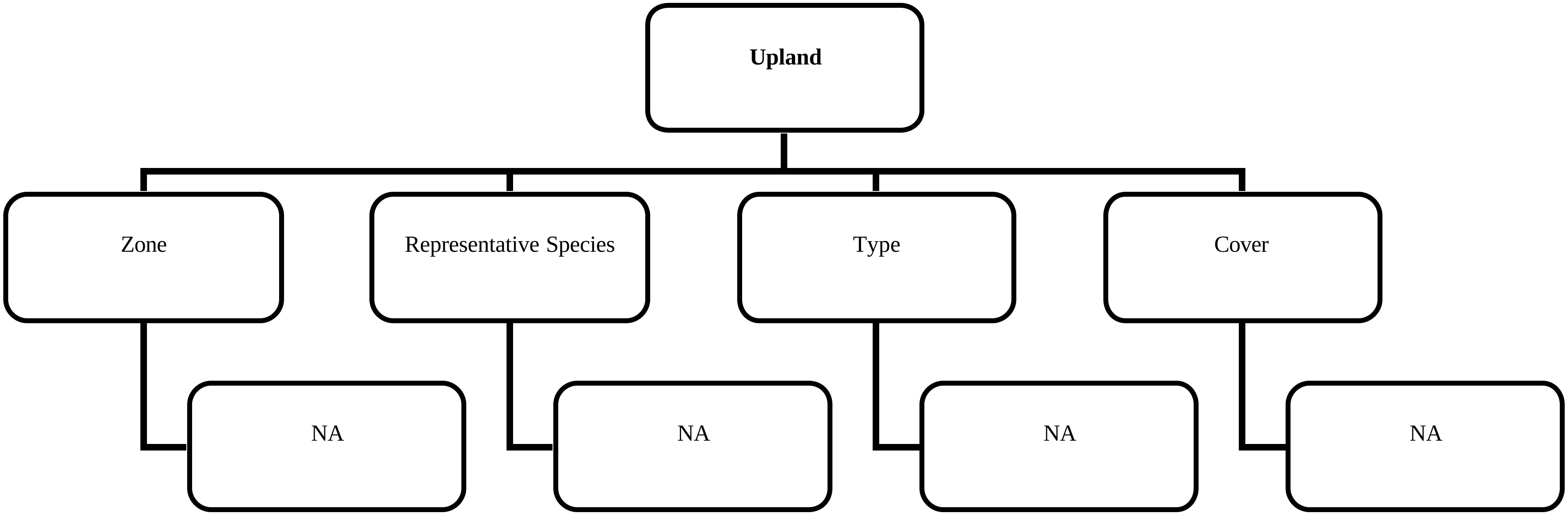

Figure 3c. Hierarchical diagram of domain values for the subtype "Upland" in the 2004 Vegetation Mapping Geodatabase for Padilla Bay, WA.

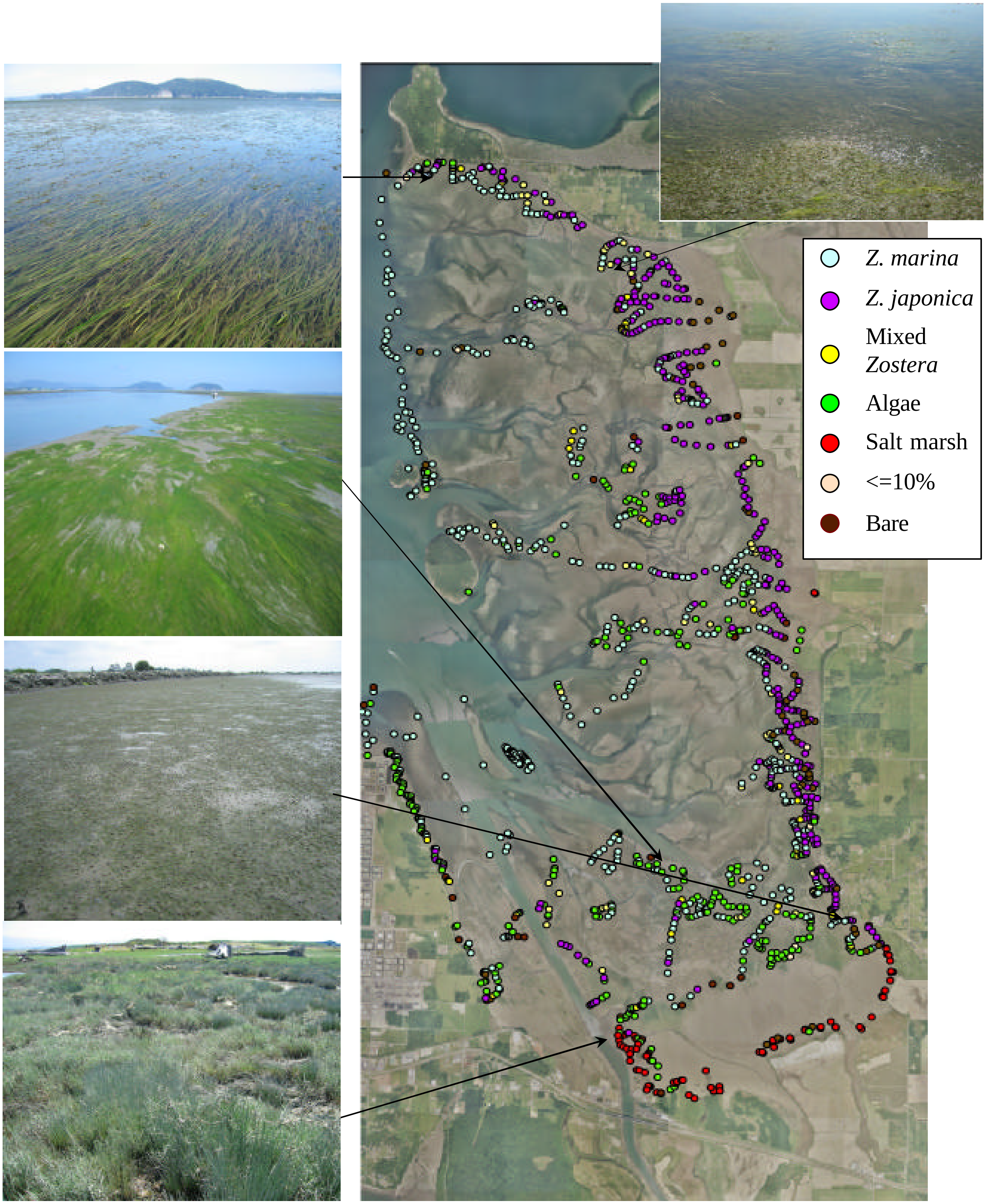

Figure 4. The color orthorectified mosaic of Padilla Bay in June 2004, with more than 1300 ground reference data sites overlaid and categorized by habitat type. Five sample photos are shown of the more than 900 linked digital photos taken in the field.

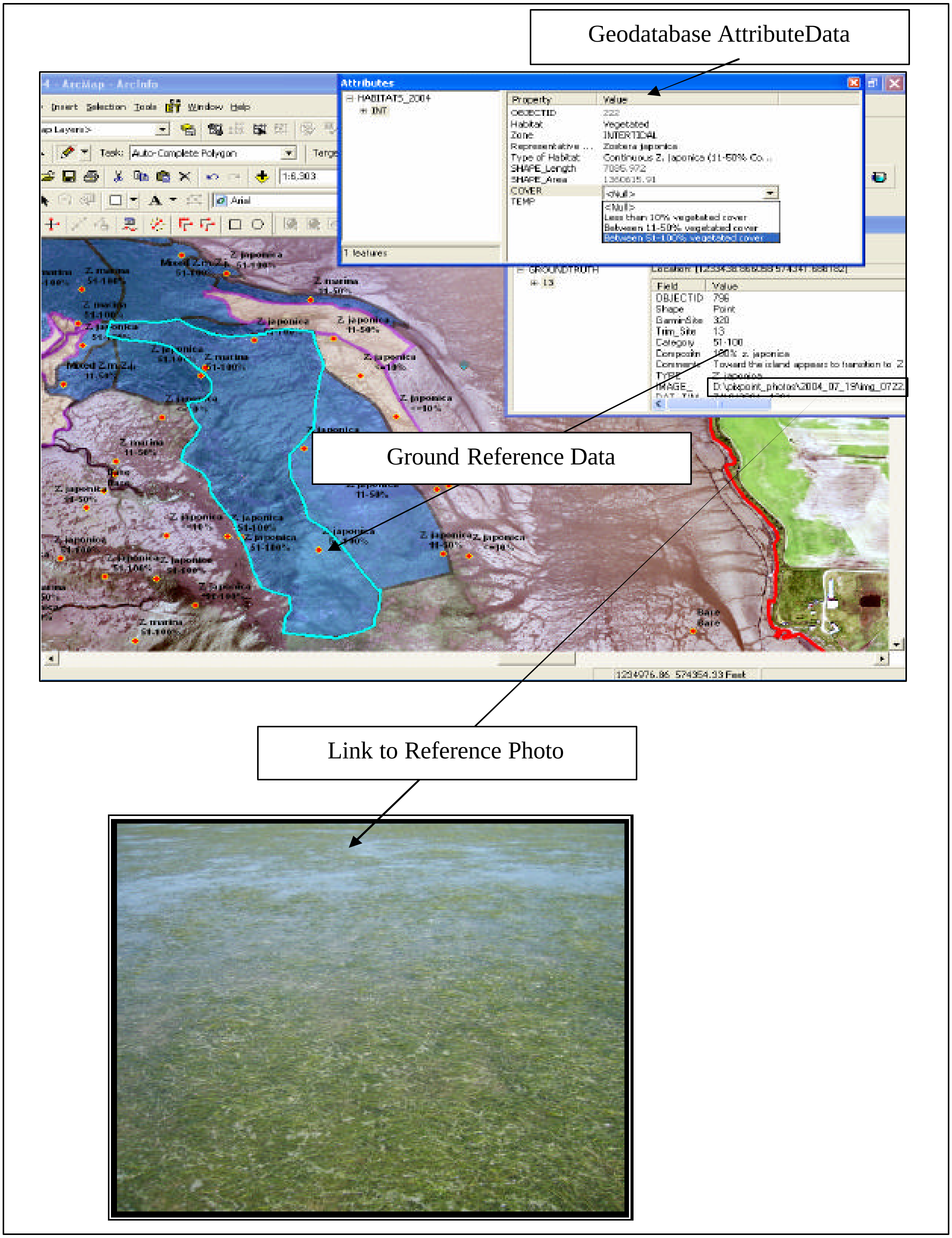

Figure 5. Ground reference field data and on-site digital photography were used to guide the on-screen interpretation. The delineated polygon was then attributed using the 2004 Vegetation Mapping Geodatabase for Padilla Bay.

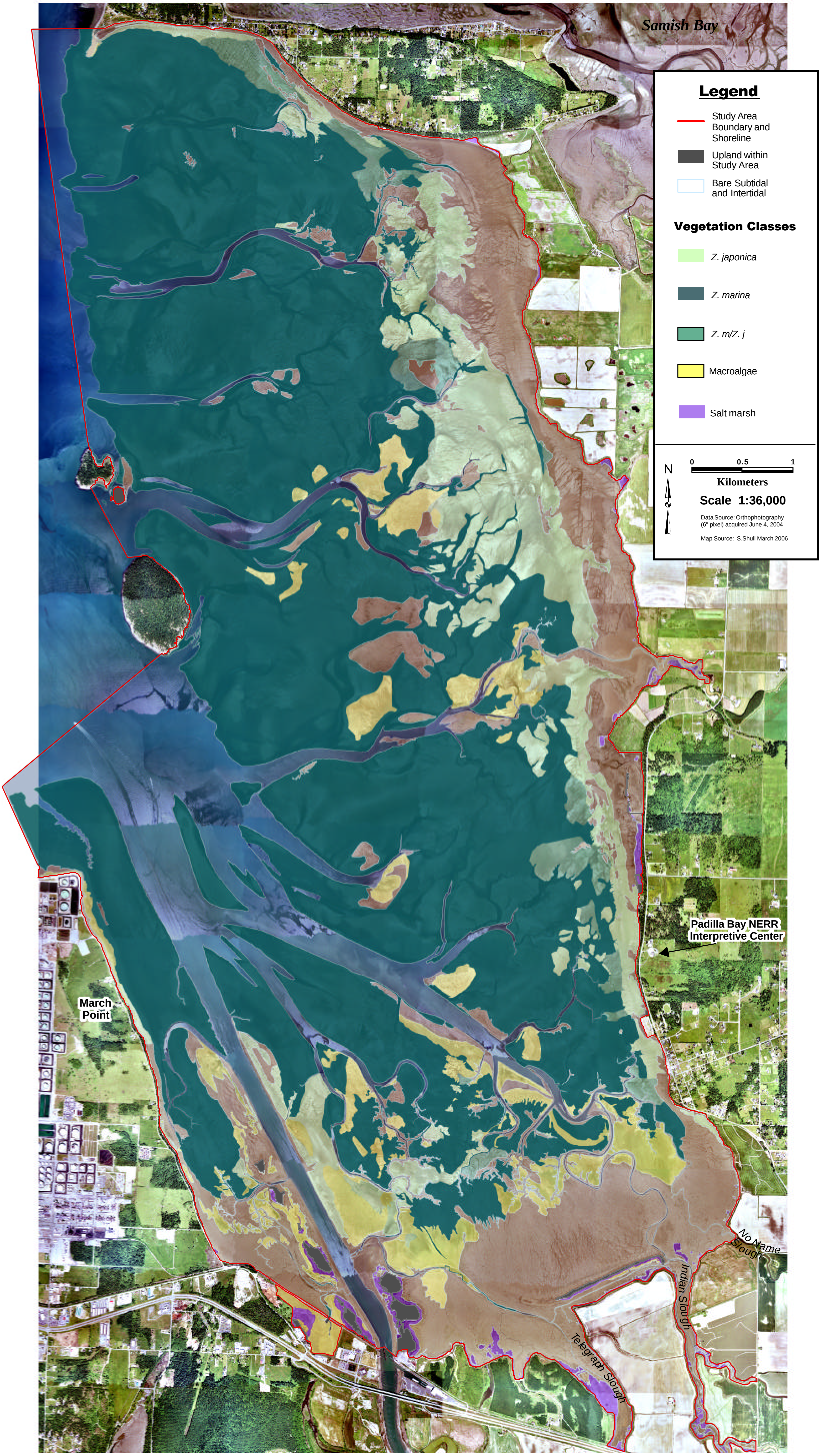

Figure 6. Distribution of eelgrasses, macroalgae, and salt marshes in Padilla Bay, Washington in June 2004.

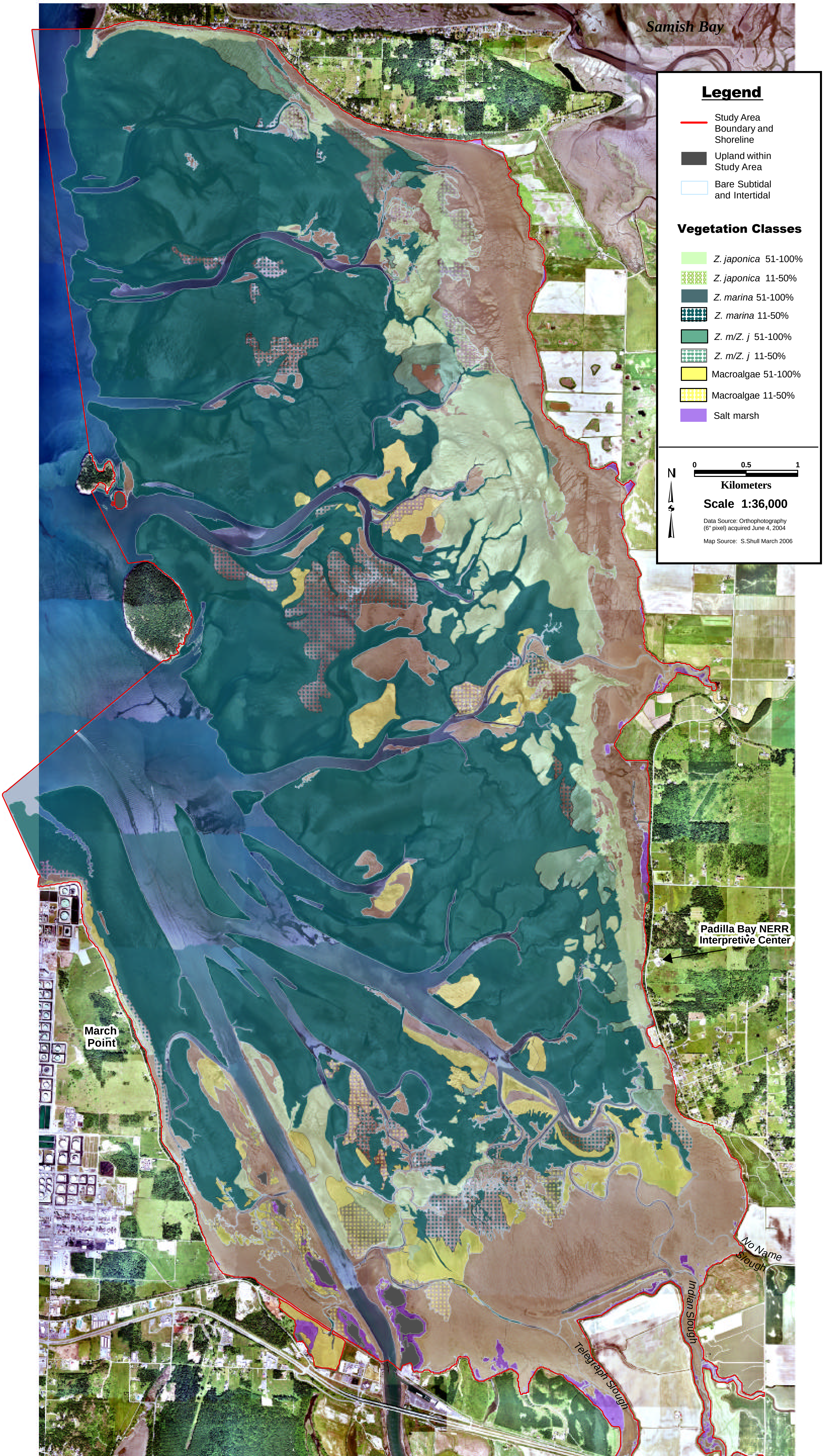

Figure 7. Distribution of all percent cover classes of eelgrasses, macroalgae, and salt marshes in Padilla Bay, Washington in June 2004.